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HEAT EXCHANGE DURING ENCAPSULATION IN A CHEMICAL WARFARE AGENT PROTECTIVE PATIENT WRAP IN FOUR HOT ENVIRONMENTS

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

APRIL 1987

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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The purpose of this study was to determine safe encapsulation time limits in four hot environments including a simulated solar heat load and thereby generate an equation predicting safe time limits for hot environments. Eight male subjects were studied during encapsulation in a Chemical Warfare Agent Protective Patient Wrap in each of four environments. The dry insulative (I_t) value of the wrap was 1.44 clo and the permeability index (I_m) was 0.25. The ambient temperature (T_a) in Environment I averaged 54.7°C with an average dew point temperature (T_{dp}) of 21.7°C and black globe temperature (T_g) of 68.3°C. In Environment II, T_a was 42.7°C; T_{dp} was 32.5°C and T_g was 56.3°C. In Environment III, T_a was 41.8°C; T_{dp} was 11.3°C and T_g was 57.5°C. In Environment IV, T_a was 35.7°C; T_{dp} was 27.7°C and T_g was 50.5°C. The average irradiance was 1152 $W \cdot m^{-2}$ and wind speed was 0.5 $m \cdot s^{-1}$ in all environments. Rectal temperature, mean skin temperature, mean body temperature (T_b), air temperature and T_{dp} within the wrap and wrap temperature were measured every minute. Metabolic rate (M) was measured during encapsulation by partitional calorimetry. Encapsulation time was the time

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the subject could voluntarily remain in the wrap or until his heart rate exceeded 160 beats·min^{-1} for five consecutive minutes. Evaporative heat loss (EHL) was calculated from the pre- and post-experimental weight of the subject, which had been corrected for dripped sweat. Dry heat gain (R+C) was calculated from the heat balance equation. The Table below lists the average heat balance data at the 30th min of encapsulation and total time of encapsulation in the four environments.

	$\bar{T}_b$ (°C)	EHL (W·m^{-2})	R+C (W·m^{-2})	M_{sk} (W·m^{-2})	M (W·m^{-2})	Encapsulation time (min)
I	38.1	278	-230	49	48	37
II	37.8	212	-159	54	53	49
III	37.7	239	-183	47	47	62
IV	37.6	174	-129	45	44	62

A multiple linear regression equation was calculated from those factors, which best predicted time of encapsulation. One factor was net heat flow through the skin (M_{sk}) which is a function of metabolic rate. The other two factors were the water vapor pressure within the wrap (P_{w-in}) and operative temperature (T_o), which integrates effects of dry heat exchange.

$$\text{Time} = 0.501\,(X) - 2.709(Y) - 0.834(Z) + 148.572 \quad \text{(min)}$$

Where X - M_{sk} $\quad R^2 = 0.530$
Y = P_{w-in} $\quad R = 0.730$
Z = T_o $\quad P = 0.0001$

These data show that safe encapsulation time is severely limited in Hot/Dry ~~(I)~~ and Hot/Wet ~~(II)~~ environments when a solar heat load is included. A preliminary study (n=2) shows that encapsulation time in Environment I can be extended by some 23 min by covering the wrap with two towels saturated with water. The wetted cover decreased patient body heat storage by enhancing evaporative heat loss from the surface of the wrap. The present study documents that heat injury will quickly develop in patients who are left in the sun while encapsulated in the wrap in any hot environment.

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ABSTRACT

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Where $X = M_{sk}$ $\quad R^2 = 0.530$

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These data show that safe encapsulation time is severely limited in Hot/Dry (I) and Hot/Wet (II) environments when a solar heat load is included. A preliminary study (n=2) shows that encapsulation time in Environment I can be extended by some 23 min by covering the wrap with two towels saturated with water. The wetted cover decreased patient body heat storage by enhancing evaporative heat loss from the surface of the wrap. The present study documents that heat injury will quickly develop in patients who are left in the sun while encapsulated in the wrap in any hot environment.

INTRODUCTION

The purpose of this study was to measure heat exchange during encapsulation in a chemical warfare agent protective patient wrap (WRAP) in four environments which included a simulated solar heat load. These data were then used to generate an equation to predict safe encapsulation limits in hot environments. An earlier study (15) indicated that time of encapsulation would be significantly diminished in a hot environment because of excessive heat strain which is exacerbated by the high insulative value and low water vapor permeability of the WRAP. That laboratory simulation of the hot environment (ambient temperature = 49.1 $\pm$ 0.4°C, dew point temperature = 17 $\pm$ 0.3°C) did not include effects of a solar heat load. Radiant heat from the sun cannot be completely or even substantially blocked during a large scale field operation. Therefore, in the present study, the time limit for WRAP encapsulation was investigated in environments which included a simulated solar heat load. The data from these experiments were then fitted to a multiple linear regression equation which best predicted time of safe encapsulation before heat injury occurred from directly measured and calculated biophysical parameters (operative temperature and water vapor pressure within the WRAP) and a factor in the heat balance equation (net heat flow through the skin, M_{sk}).

MATERIALS AND METHODS

Eight male members of the U. S. Marine Corps volunteered to be subjects for these experiments. Both written and verbal descriptions of the experiments were given to the subjects before they consented to do the experiments. Individual characteristics of the subjects are shown in Table 1.

Table 1. Individual characteristics of the subjects.

	Height (cm)	Weight (kg)	Age (yr)	Body Surface (m^2)	Body Fat (%)	Resting Metabolic Rate ($W \cdot m^{-2}$)
1	173.5	67.7	31	1.81	15.6	28.0
2	173.0	59.7	22	1.71	9.8	24.0
3	171.0	88.9	27	1.99	24.4	48.3
4	179.0	68.1	29	1.86	9.5	53.5
5	169.0	63.6	26	1.73	18.0	42.6
6	182.0	68.9	22	1.90	11.8	57.0
7	169.0	70.2	24	1.80	14.3	43.6
8	175.0	73.8	28	1.89	14.0	47.6
$\bar{X}$	173.9	70.1	26.1	1.84	14.7	43.1
S.D.	4.6	8.7	3.3	0.1	4.9	11.6

Each subject was studied in each of four environmental conditions with experiments at least four days apart to limit effects of heat acclimation. In every condition, an infrared light bank was used to simulate a solar heat load. Wind speed was 0.5 $m \cdot s^{-1}$. The ambient temperature (T_a), dew point temperature (T_{dp}), relative humidity, ambient water vapor pressure (P_w), black globe temperature (T_g), water vapor pressure within the WRAP (P_{w-in}) and operative temperature (T_o) for each environment are listed in Table 2. Operative temperature integrates the effects of dry heat weighted by the respective convective and radiative heat transfer coefficients. T_a, T_{dp}, and T_g were measured between the two supine subjects at the level of their knees and 61 cm above the floor of the chamber. The heat lamps were located in two banks. The apex of the lights was 2.9 m above the chamber floor. The lowest level of lights was 2.6 m and was located at the head and the feet of the subject. There were 68 lamps, each lamp was 375 watts. The mean irradiance at the level of the subjects as measured by a Fritschen net radiometer was 1152 $W \cdot m^{-2}$. T_a was measured using a thermister (YSI) which was shielded from direct exposure to the heat lamps by aluminum foil. T_{dp} was measured with a dew point sensor (6). P_w was calculated from dew point temperature using the Antoine equation (13). T_g was measured with a thermister placed inside a standard black globe.

The chemical warfare agent protective patient wrap was composed of an impermeable ground sheet made of Loretex and nylon and an upper blanket made of 3M Melt Blown Polypropylene in a Nyco twill shell. There was a window in the WRAP which was made of tri-laminated nylon/saran/polyethylene film. The dry insulative (I_t) value of the WRAP was 1.44 clo (0.22 $m^2 \cdot K \cdot W^{-1}$), and the water vapor permeation constant (i_m) was 0.25 (3) with a resultant i_m/clo

Table 2. Mean (± standard deviation) physical conditions of the four environments

	T_a (°C)	T_{dp} (°C)	rh (%)	P_w (kPa)	T_g (°C)	T_o (°C)	P_{w-in} (kPa)
I	54.7 (1.5)	21.7 (0.7)	17	2.6 (0.1)	68.3 (0.9)	65.4 (0.8)	9.8 (3.2)
II	42.7 (1.5)	32.5 (0.9)	58	4.9 (0.3)	56.3 (0.3)	53.6 (2.2)	8.1 (0.6)
III	41.8 (0.7)	11.3 (0.4)	16	1.3 (0.0)	57.5 (0.8)	55.5 (1.1)	6.6 (1.0)
IV	35.7 (0.9)	27.7 (0.5)	63	3.7 (0.1)	50.5 (1.0)	49.2 (1.0)	7.3 (1.0)

value of 0.17. A cardboard frame was placed inside the WRAP to prevent the film of the window from falling directly on the subject's face, as occurred in a previous study (15). The WRAP contained two ports, one on each side at the level of the subject's chest through which were passed the electrical lines for the instruments and the expired air hose.

Prior to the study, resting metabolic rate of the fasted subject was measured while the subject was in a supine position (Table 1). The subjects also completed a familiarization session which was a shorten version of an actual experiment that included encapsulation and exposure to the heat lamps.

For the actual experiments the order of environmental conditions was counterbalanced. Two subjects were studied during each experiment which began at approximately 1700 h. At approximately 1700 h, the normal circadian rhythm in body temperature is near the zenith, which has been reported as some 0.4^{o}C higher than occurs at 0800 h (14). Initiation of the thermoregulatory effectors also occurred at a higher core temperature in the late afternoon than in the morning (14). Consequently, the core temperature data reported in this study are approximately 0.4^{o}C higher than data collected in morning experiments.

The subject dressed in gym shorts, then inserted a thermister (YSI) into his rectum to a depth of 10 cm. Body weight was then measured. ECG electrodes were attached to his chest for subsequent heart rate measurement. Each subject lay on the ground cover of the WRAP which had been placed on a standard Army litter outside the environmental chamber. Skin thermocouples (copper-constantan) were attached at eight sites. A plastic beaker which contained a dew point sensor was placed between the knees of the subject. Equilibration of the dew point sensor with the air within the WRAP was

achieved through numerous holes which were bored in the beaker. A thermocouple for the measurement of air temperature within the WRAP was attached to the beaker. A Daniels valve with an affixed mouthpiece and a nose clip were placed in the wrap within reach of the subject. A small diameter tube was placed between the eyebrows and attached to the subject. Oxygen and carbon dioxide concentration within the WRAP was monitored through this tube. The upper blanket of the WRAP was placed over the legs of the subject while he rested quietly until his rectal temperature was stable. This equilibration time was approximately 30 min, but was longer in some cases.

After equilibration, Arctic Ray-Ban sunglasses (Bausch and Lomb) were placed on the subjects to prevent eye injury from the heat lamps. The subjects were then encapsulated in the WRAP and taken into the environmental chamber. The litters were placed in previously marked positions and the positions were the same for each experiment to standardize the amount of radiative heat received by each subject.

Rectal temperature (T_{re}), skin temperatures, T_{dp} within the WRAP, air temperature within the WRAP, T_a, T_{dp} and T_g were measured every minute. Oxygen and carbon dioxide concentrations were periodically measured within each WRAP throughout the experiment using a Horizon II System (Sensormedics). Heart rate was measured by telemetry (Hewlett-Packard). Metabolic rate was measured at least once during encapsulation by open circuit spirometry using the Horizon II System.

The experiment was terminated when the subject's heart rate was 160 beats $\cdot$ min^{-1} for 5 min, T_{re} was 39.0^{o}C or when the subject felt unable to continue the experiment. The time the subject remained encapsulated in the

wrap while he was in the environment chamber is referred to as encapsulation time.

Immediately after the experiment, the subject was carried out of the environmental chamber. The WRAP was opened. T_{re} and heart rate were monitored throughout recovery. When the subject recovered sufficiently from the heat stress, he was weighed.

Total body sweating rate ($g \cdot min^{-1}$) was calculated from pre- and post-experiment body weights corrected for the unevaporated sweat. The unevaporated sweat was measured by weighing the WRAP before and after the experiment.

Mean skin temperature was calculated as:

$$\bar{T}_{sk} = 0.07\ (T_{head}) + 0.175\ (T_{chest}) + 0.175\ (T_{back}) + 0.07\ (T_{upper\ arm}) + 0.07\ (T_{forearm}) + 0.05\ (T_{hand}) + 0.19\ (T_{thigh}) + 0.20\ (T_{calf}) \quad \text{(Eqn. 1)}$$

Mean body temperature was calculated from T_{re} and $\bar{T}_{sk}$ as:

$$\bar{T}_b = 0.9\ (T_{re}) + 0.1\ (\bar{T}_{sk}) \quad \text{(Eqn. 2)}$$

Heat balance was calculated for each individual at 30 min of encapsulation using the equation:

$$S = M_{sk} - (\text{sensible heat loss, R+C}) - (\text{skin evaporation, } E_{sk}), W \cdot m^{-2} \quad \text{(Eqn. 3)}$$

$$\text{or } S = M_{sk} - hF_{cl}(\bar{T}_{sk} - T_o) - wh_eF'_{pcl}(P_{s,sk} - P_{w\text{-}in})$$

where S is the rate of body heat storage ($W \cdot m^{-2}$); M_{sk} is the net heat flow determined from (Metabolism (M)-Work-C_{res}-E_{res}) with the latter two factors being dry heat loss and evaporative heat loss from the lungs (4); hF_{cl} and $h_eF'_{pcl}$ are the combined radiative and convective heat transfer coefficient that govern sensible heat exchange and the evaporative heat transfer

coefficient involving insensible heat exchange (9) respectively; w is the equivalent fraction of the total body surface (A_D) wet with sweat which was calculated from E_{sk}/E_{max} (12); $P_{s,sk}$ is the saturation vapor pressure (kPa) at mean skin temperature ($\bar{T}_{sk}$); and P_{w-in} is the water vapor pressure within the WRAP (kPa) calculated from dew point temperature. The effective combined radiative and convective heat transfer coefficient (hF_{cl}) was calculated from the equation:

$$(M - E)\cdot(\bar{T}_{sk} - T_o)^{-1} \qquad \text{(Eqn. 4)}$$

F'_{pcl} was calculated using the equation:

$$(1)\cdot(1 + 0.318\ h_c\ I_t)^{-1} \qquad \text{(Eqn. 5)}$$

where I_t = 1.44 clo for the WRAP. The convective heat transfer coefficient (h_c) was calculated from the equation:

$$h_c = 8.3v^{.5} \qquad \text{(Eqn. 6)}$$

where wind velocity (v) was 0.3 $m\cdot s^{-1}$ in these experiments. The operative temperature (T_o) of the environment was calculated from the equation:

$$T_o = (h_r\bar{T}_r + h_cT_a)\cdot(h_r + h_c)^{-1} \qquad \text{(Eqn. 7)}$$

where $\bar{T}_r$ is the mean radiative temperature and is calculated by the equation:

$$\bar{T}_r = T_g + 2.2\sqrt{v}(T_g - T_a) \qquad \text{(Eqn. 8)}$$

In every case w was unity indicating that the body was completely covered with sweat.

One way analyses of variance with repeated measures were used to compare the parameters of the heat balance equation and body temperatures. Two way analyses of variance with repeated measures were used to compare differences between the first and 30th min temperatures. Tukey's test of critical difference was used where appropriate. A linear regression equation describing mean body temperature over time was used to calculate the change

in body heat content. A multiple linear regression equation (BMDP) was generated which predicted time of encapsulation from M_{sk}, P_{w-in}, and T_o. All differences are reported at $P < 0.05$.

In the environments studied, encapsulation was quite short, especially in Environment I (Table 2). Gonzalez et al. (8) predicted that heat exchange would be improved through the use of a wettable cover over chemical protective garments. To investigate this theory, two volunteers were retested in Environment I. The protocol was the same as described above with the addition of a wetted cover. The covers used were two 100% cotton olive green towels. Each towel was 52.1 cm x 90.8 cm with I_t equal to 1.24 clo and a permeability index of 0.47 (3). The towels were saturated with water and placed end to end, almost covering the WRAP of each subject. The towels were wetted again every 15 min. Evaporation of water from the towels was measured from pre- and post cover weights. It should be noted that the developer reported that wettedness will not reduce the chemical agent protection of the WRAP. Termination criteria were the same for this experiment as for the other experiments.

RESULTS

There was significant heat storage during encapsulation in the four environments. $\bar{T}_{sk}$, T_{re}, and $\bar{T}_b$ increased significantly from the first min of encapsulation (Table 3) to the 30th min (Table 4). Although in Environment I, T_{re} and $\bar{T}_{sk}$ were greater at 30 min than in the other three environments (Table 4), $\bar{T}_b$ increased more in I than in III and IV. This greater heat storage was due to the excessive dry heat gained from the environment in I. The increase in $\bar{T}_b$ per min of encapsulation was greatest in I although only significantly different from III and IV (Table 4). There was also a larger

Table 3. Mean (± standard deviation) rectal, skin and body temperatures during the first min of encapsulation in the four environments.

	Ta/%rh	T_{re} (°C)	$\bar{T}_{sk}$ (°C)	$\bar{T}_b$ (°C)
I	54.5/17%	37.41	36.60[a]	37.31
		(0.2)	(0.4)	(0.1)
II	43/58%	37.36	36.43	37.20
		(0.3)	(1.2)	(0.2)
III	42/16%	37.46	36.04	37.32
		(0.2)	(1.4)	(0.3)
IV	36/63%	37.44	35.92	37.29
		(0.2)	(1.0)	(0.2)

[a]I is greater than III and IV.

Table 4. Mean (± standard deviation) temperatures and components of the heat balance equation at 30 min of encapsulation.

	T_{re} (°C)	T_{sk} (°C)	T_b (°C)	$\Delta T_b/\Delta t$ (°C·min^{-1})	Evaporative Heat Loss (W·m^{-2})	C_{res} (W·m^{-2})	R+C (W·m^{-2})	M_{sk} (W·m^{-2})	M (W·m^{-2})	Encapsulation Time (min)
I	37.8	40.2[a]	38.1[b]	0.044[b]	277.8[d]	-1.25[f]	-230[d]	49.1	47.9	38.4[b]
	0.2	1.3	0.2	0.01	29.9	0.3	37	7.6	7.6	5.0
II	37.6	39.1	37.8	0.039[c]	212.1	-1.01	-159	54.2	53.2	49.3
	0.3	0.7	0.3	0.01	57.6	0.3	54	9.9	9.8	8.6
III	37.6	38.5	37.7	0.030	229.8[e]	-1.02	-183[e]	48.0	47.0	61.6
	0.3	0.4	0.3	0.01	46.9	0.2	37	6.2	6.2	14.1
IV	37.6	38.3	37.6	0.028	173.5	-0.73	-129	45.1	44.3	61.8
	0.3	0.4	0.3	0.01	46.8	0.2	46	3.8	3.7	13.2

[a]I is different from II, III, IV

[b]I is different from III, IV.

[c]II is different from III, IV.

[d]I is different from II, IV.

[e]III is different from IV.

[f]I is different from IV.

Table 5. Mean (± standard deviation) rectal, skin and body temperatures and heart rate during the last min of encapsulation.

	Ta/%rh	T_{re} (°C)	$\bar{T}_{sk}$ (°C)	$\bar{T}_b$ (°C)	HR (beats•min^{-1})
I	54.5/17%	38.1	40.0	38.4	135
		(0.4)	(0.5)	(0.4)	(25)
II	43/58%	38.4	39.9	38.4	138
		(0.2)	(0.9)	(0.4)	(19)
III	42/16%	38.4	39.3	38.5	135
		(0.4)	(0.6)	(0.4)	(21)
IV	36/63%	38.4	39.1	38.5	139
		(0.4)	(0.2)	(0.3)	(20)

increase in $\Delta\bar{T}_b/\Delta t$ ($^{o}C \cdot min^{-1}$) in II than in III and IV (Table 4). Table 5 shows the final T_{re}, $\bar{T}_{sk}$, and $\bar{T}_b$ measured before the experiment was terminated. The measured water loss, unevaporated sweat and evaporative rate for each environment are presented in Table 6. The total water loss was significantly less in Environment IV than in the other three environments, while the evaporative rate was highest in Environment I.

Time of encapsulation could be predicted from biophysical parameters and a factor in the heat balance equation using a multiple linear regression equation.

$$\text{Time} = -0.501(M_{sk}) - 2.709(P_{w\text{-}in}) - 0.834(T_o) + 148.572 \qquad \text{(Eqn. 9)}$$

$$R^2 = 0.530$$

$$R = 0.73$$

$$p < 0.0001$$

M_{sk} is a function of the metabolic rate calculated from the heat balance equation. $P_{w\text{-}in}$ is the water vapor pressure within the WRAP itself which was calculated from the dew point temperature. T_o integrates the environment in terms of dry heat stress.

Fig. 1 compares the $\bar{T}_b$ of one encapsulated subject covered with the wet towels in Environment I with his $\bar{T}_b$ during encapsulation in the same environment without the wetted cover. Time of encapsulation was increased in this individual by almost 30 min, and averaged some 23 min for both subjects. $\bar{T}_b$ increased at a less rapid rate (0.0287 vs.0.0331 $^{o}C \cdot min^{-1}$) when the WRAP had a wetted cover, with the mean from two subjects being 0.0287 vs. 0.0378$^{o}C \cdot min^{-1}$ with and without the wetted cover, respectively. There was also a lag in the time where $\bar{T}_b$ started to increase which was 12 min longer than without the wetted cover. Table 7 shows the advantages of using a wetted cover in Environment I for the two subjects studied.

Table 6. Mean (± standard deviation) measured water loss, sweat drippage and evaporative rate.

	T_a/%rh	Measured Water Loss ($g \cdot min^{-1}$)	Measured Drip ($g \cdot min^{-1}$)	Measured Evaporative Rate ($g \cdot min^{-1}$)	Drip / Sweating Rate (%)	Evaporative Rate / Sweating Rate
I	54.5/17%	16.38	3.79[b]	12.6[c]	23	77
		(1.4)	(0.9)	(1.4)		
II	43/58%	15.75	6.11	9.6	39	61
		(3.7)	(2.8)	(2.8)		
III	42/16%	15.18	4.74	10.4[d]	31	69
		(3.5)	(1.9)	(2.0)		
IV	36/63%	12.63[a]	4.73	7.9	37	63
		(3.1)	(1.7)	(2.2)		

[a]IV less than I, II, III.
[b]I less than II.
[c]I is greater than II, III, IV.
[d]III is greater than IV.

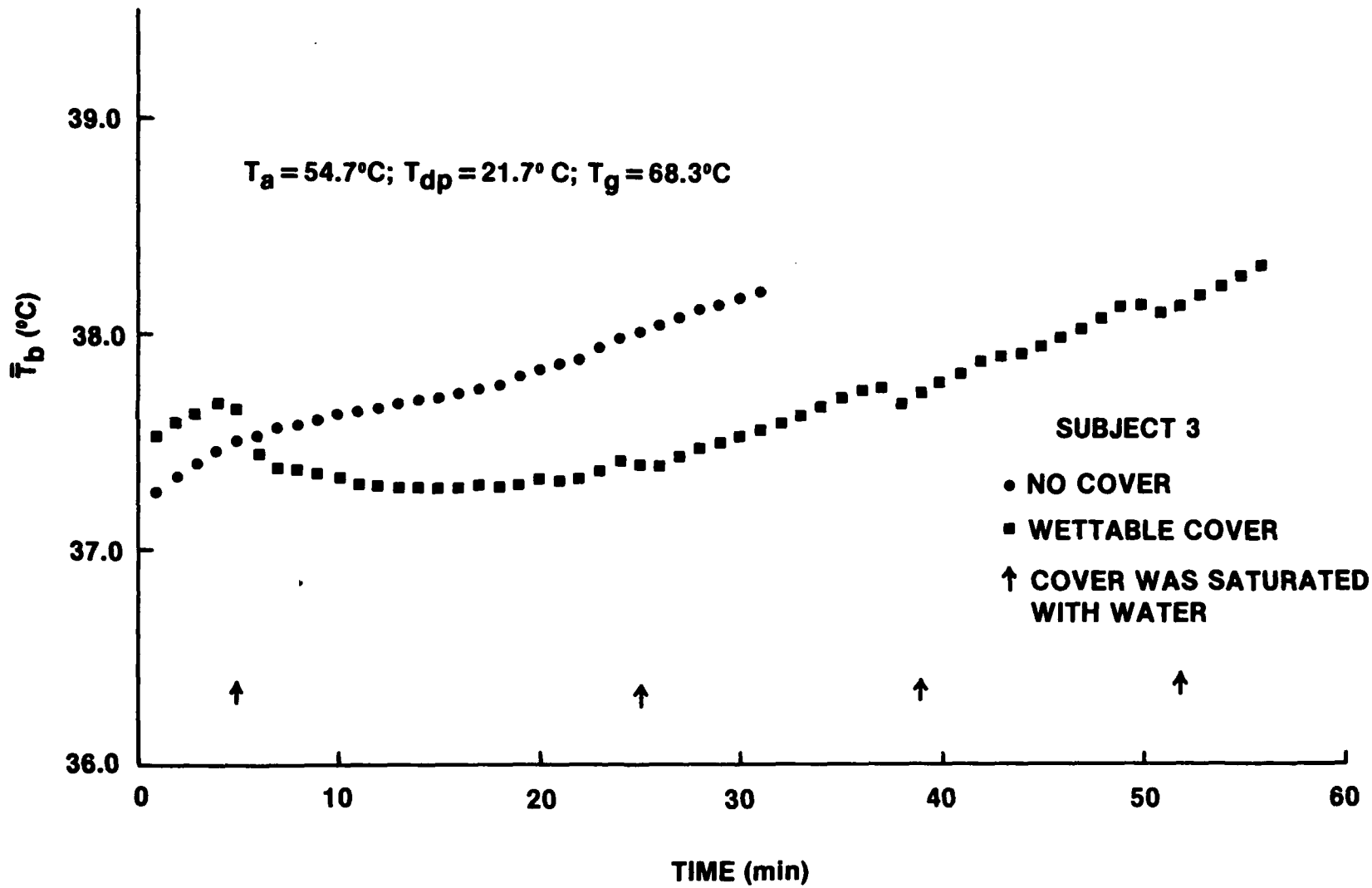
$T_a = 54.7°C$; $T_{dp} = 21.7°C$; $T_g = 68.3°C$
$\bar{T}_b$ (°C)
39.0
38.0
37.0
36.0
0
10
20
30
40
50
60
TIME (min)
SUBJECT 3
• NO COVER
▪ WETTABLE COVER
↑ COVER WAS SATURATED WITH WATER

Table 7. Mean body temperature, dry heat gain, evaporative heat loss, metabolism at min 30 and evaporative heat loss from the towel during wetted cover experiment in Environment I (54.5°C/17% rh)

	$\bar{T}_b$ (°C)	$\Delta\bar{T}_b/\Delta t$ (°C•min^{-1})	R+C (W•m^{-2})	E_{sk} (W•m^{-2})	M (W•m^{-2})	E_{tow} (W•m^{-2})	Encapsulation Time (min)
			WETTABLE COVER				
S_3	37.42	0.0287	-103.0	168.8	65.8	237.3	60
S_6	38.00	0.0286	-243.0	271.5	38.3	215.5	51
			NO WETTABLE COVER				
S_3	37.96	0.0331	-193	246.5	53.7	-	33
S_6	37.25	0.0424	-284	322.7	39.1	-	33

DISCUSSION

The data presented in Tables 4, 5 and 6 indicate that all environments studied were severely limiting to the encapsulated subject. The purpose of these experiments was to generate a predictive equation which might be used to estimate tolerable encapsulation time limits in a hot environment. The net heat flow through the skin (M_{sk}), P_{w-in}, and T_o were the three factors which best fit a multiple linear regression equation predicting time of encapsulation (Eqn. 9). M_{sk} is a direct function of the metabolic rate calculated from the heat balance equation and can be predicted from the height and weight of the subject. P_{w-in} is the water vapor pressure within the WRAP itself which was calculated from the dew point temperature or relative humidity of the environments. T_o describes the environment in terms of dry heat. Two parameters, P_{w-in} and T_o, can be calculated for an environment if T_a, T_{dp}, rh, and T_g are known. Consequently, all of the parameters used in the prediction of encapsulation time are easily measured or can be calculated for any hot environment.

Equation 9 only explains approximately 53% of the variation in encapsulation time, even though it is highly significant ($p<0.0001$). Physiological data generally are quite variable due to the heterogeneity in human subject size and, in part, due to a motivational factor. For example, one subject, a heavy smoker, invariably was anxious during the experiment. He usually asked to be removed from the WRAP before his core temperature or heart rate were increased to the point where the experiment should have been terminated. Unavoidable motivational factors would increase the variation in the data. Furthermore, the regression equation should be strictly for use in hot environments (primarily with a marked radiative heat load) because it

would not necessarily predict encapsulation time in a cool environment accurately. Equation 9 seriously underestimated encapsulation time in a moderate environment with no radiative heat load in a previous study (T_a = 30°C, T_g = 30°C, T_{dp} = 7°C) (15). On the other hand, the regression equation underestimated the encapsulation time in a hot dry environment (T_a = 50°C, T_g = 50°C, T_{dp} = 17.0°C) by approximately thirty minutes. The predicted time of encapsulation was calculated to be 61 min, while experimental time of encapsulation averaged 92 min (15). It is clear that there are limits to the use of the regression equation as a predictor of encapsulation time and the equation is only appropriate in hot environments, or in more moderate environments with a solar heat load.

In all four environments studied there was a significant amount of water lost from sweating which ranged from an average of 0.5 kg in Environment I to 0.4 kg in Environment IV (Table 6). These results show that patients encapsulated in the WRAP for even a short period of time in the heat will become dehydrated and will need fluid replacement. Estimation of fluid replacement to a patient enclosed in the WRAP must included that lost as sweat in addition to normal fluid replacement. Of course, it must be remembered that injuries and shock have already occurred if the WRAP is being used. Loss of blood, in addition to the trauma of the injury, will seriously decrease the capacity of the patient to withstand the dehydration which will occur as a result of encapsulation in a hot environment or any moderate environment with a marked radiative heat load.

Prior to injury, some of the patients may have been injected with atropine. Atropine will significantly reduce sweating through competitive inhibition of acetylcholine at the muscarinic receptor of the sweat gland

(16). In studies of unacclimated men exercising in warm or hot environments (1,10,11) atropine reduced sweating by 45% of control sweating rates. If evaporative heat loss were reduced to that extent during encapsulation then heat storage would be significantly increased because evaporative heat loss accounted for all heat loss in this study (Table 4). Heat storage would increase by 126 $W \cdot m^{-2}$ if evaporation was decreased by 45% of control in Environment I. The $\Delta T_b/\Delta t$ would increase by $0.0201^{o}C \cdot min^{-1}$ and encapsulation time would decrease to 26 min. Heat storage would increase 97 $W \cdot m^{-2}$ if atropine had been used in Environment II and time of encapsulation would be decreased to 35.5 min. Further calculations show that the decreased evaporative heat loss expected with atropine treatment would increase heat storage in Environments III and IV by 105 and 79 $W \cdot m^{-2}$ respectively. Calculated time would be reduced to 39.6 min in Environment III and 42.7 min in Environment IV. The predicted decrease in encapsulation time with atropine treatment in the four environments averaged 69% of the observed encapsulation time.

In the field, the sun is primarily a point source of heat whereas the bank of infrared lights used in the present study provided numerous sources of heat, thereby resembling a cloudy sky. Also, the emission spectrum of the infrared lights was probably different from that of the sun (2,5,7). Yet the simulated heat load as measured by the net radiometer (1152 $W \cdot m^{-2}$) approximated desert maximal solar incidence. Consequently, time of encapsulation in the four environments studied estimated tolerable encapsulation time of well-hydrated, uninjured subjects in the field.

The present study documents that excessive heat storage occurred during encapsulation in the WRAP in all environments studied (Tables 4, 5, and 6).

Average time of encapsulation in Environment I which included the simulated solar heat load was 38 min. This environment was very similar to that of our previous study (15), which did not include a radiant heat load. The average encapsulation time in that study was 92.3 min. Clearly, the simulated solar heat load severely decreased safe encapsulation time. In the field it will be nearly impossible to block all sources of solar radiation especially diffuse or terrain-reflected radiation. In some cases, encapsulated patients may be exposed to direct sunlight. Given the very limited time for safe encapsulation (38 min) of healthy subjects in a HOT/DRY environment with a simulated radiant heat load, we felt that it was necessary to find a method to prolong encapsulation time. Gonzalez et al. (8) have recently described the cooling benefit of using a wettable cover over chemical protective garments which was calculated to increased skin heat loss. The thermoregulatory benefit of placing a wet cover over the WRAP in Environment 1 can be seen in Fig. 1 and Table 7. Encapsulation time was increased by an average of 65% in the two subjects studied, and the evaporative heat loss was increased by 58% through the use of the wetted cover. Heat storage was decreased from $0.0378^{o}C \cdot min^{-1}$ to $0.0287^{o}C \cdot min^{-1}$. An average of 600 g of water was evaporated from the cover, although approximately 2000 g of water was used to throughly saturate the two towels covering each wrap. Gonzalez et al. (8) predicted from their model based on data obtained from heat transfer studies using an upright copper manikin that at least 32 $g \cdot min^{-1}$ of water would be required to maintain a wet cover in Environment I. Approximately 10 $g \cdot min^{-1}$ was evaporated from the wet cover in this experiment, which covered only the top side of the WRAP. The cover was re-saturated with water approximately every 15 min, which may have been too

infrequent to maximize evaporation from the cover. Nonetheless, this experiment clearly demonstrates the increased cooling achieved by covering the encapsulated subject with two wet towels and periodically rewetting the towels. In those cases where there has been atropine treatment prior to encapsulation, the use of a wettable cover over the WRAP appears obligatory in a hot/dry environment.

CONCLUSIONS

Exposure to a simulated solar heat load during encapsulation in a chemical warfare agent protective patient wrap severely limited the time the subjects could remain in the WRAP. The time of safe encapsulation in an environment which included a simulated solar heat load was best predicted from operative temperature (T_o), ambient water vapor pressure within the WRAP (P_{w-in}) and net heat flow through the skin (M_{sk}). Encapsulation time was prolonged by some 23 min in Environment I when a cover saturated with water was placed over the WRAP.

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